Mass of the $D\_s(0^+, 1^+)$ system

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On the mass of the $D_s(0^+, 1^+)$ system

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In this note we discuss a determination for the mass of the $D_s(0^+, 1^+)$ system recently discovered by the BaBar, CLEO II and Belle Collaborations. The value of the mass is derived by making explicit the prediction obtained in a quark-meson model prior to the discovery of these states.

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Recently the BaBar collaboration [1] discovered a narrow meson near 2.32 GeV/c^2 decaying into $D_s\pi^0$. The reported mass is

$$M = 2316.8 \pm 0.4\,\mathrm{MeV}/c^2\ , \tag{1}$$

while the width $\Gamma = 8.6 \pm 0.4$ MeV/c^2 is consistent with the experimental resolution. This result has been confirmed by the CLEO II Collaboration [2] and the Belle Collaboration [3]. Besides the 2.32 state CLEO also finds another narrow state, near 2.46 GeV/c^2, decaying into $D_s^*\pi^0$. More precisely for the latter mass they find

$$M' = 2463\,\mathrm{MeV}/c^2\ . \tag{2}$$

These data have triggered a discussion on the nature of the observed states, see e.g. [4–16] and the review in [17]. The natural interpretation should be that these states form the $J^P = (0^+, 1^+)$ doublet, predicted by the Heavy Quark Effective Theory (HQET) [18] and generally denoted as S in this formalism. Their masses happen to be below the threshold mass for the decay into the Zweig allowed final state $D^{(*)}K$ and this forces the isospin violating $D_s^{(*)}\pi^0$ decay channel and the narrowness of the decaying meson. Though straightforward, this identification is questioned by some results of potential models [19–21] that predict larger masses, above the $D^{(*)}K$ threshold. Because of it, more exotic explanations have been proposed in terms of baryonium, $D\pi$ atoms or DK molecules [4–8].

Our point of view is very close to the one expressed in [9] (see also [22]). We do not see anything exotic in this state, especially so because the mass $M_S^{(s)}$ of the $S = (0^+, 1^+)$ multiplet in the strange sector can be obtained using a relativistic quark model incorporating the symmetries of the HQET [23]. The calculation is entirely analogous to the one of the non-strange multiplet $(0^+, 1^+)$ whose mass was predicted in [23]:

$$M_S = 2165 \pm 50\,\mathrm{MeV}/c^2\ . \tag{3}$$

A rough estimate of the strange $S-$doublet mass can be simply obtained by adding a mass term

$$M(D_s) - M(D) \simeq M(D_s^*) - M(D^*) \simeq 100\,\mathrm{MeV}/c^2 \tag{4}$$

to (3). This would give a result $M_S^{(s)} \simeq 2265$ MeV/c^2, which would be compatible with (1) and (2) only if the theoretical uncertainties were larger. This estimate is however too crude, and in any case unnecessary because the model allows a more precise calculation. In view of its interest we present it below. It is worth noticing that not only the average mass (3) of the $J^P = (0^+, 1^+)$ non-strange states was computed, but also the masses of the strange $J^P = (0^+, 1^+)$ states were already evaluated by us. This calculation is contained in [24] and its result was used as a parameter in a form factor parametrization. In this note we briefly recall the discussion outlined in [24] and make explicit the prediction for $M_S^{(s)}$.

The model we consider is a quark-meson model (CQM), introduced in [23] as an extension of the ideas and the methods in Refs. [22], [25] and [26]. A survey of these topics can be found in [27]. The transition amplitudes containing light/heavy mesons in the initial and final states as well as the couplings of the heavy mesons to hadronic currents can be calculated via quark loop diagrams where mesons enter as external legs. The model is relativistic and incorporates, besides the heavy quark symmetries, also the chiral symmetry of the light quark sector.

The model can be extended to the strange quark sector solving the gap equation discussed in [28] with a non zero current mass for the strange quark:

$$\Pi(m) = m - m_0 - 8\,m\,G\,I_1(m^2) = 0, \tag{5}$$

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where $G = 5.25$ GeV^{-2} and m_0 is the current mass of the strange quark. The I_1 integral is calculated using the proper time regularization:

$$I_1 = \frac{iN_c}{16\pi^4}\int^{\text{reg}} \frac{d^4k}{(k^2-m^2)} = \frac{N_c m^2}{16\pi^2}\Gamma\left(-1, \frac{m^2}{\Lambda^2}, \frac{m^2}{\mu^2}\right). \tag{6}$$

The choice of the ultraviolet (UV) cutoff is dictated by the scale of chiral symmetry breaking $\Lambda_\chi = 4\pi f_\pi$ and we adopted $\Lambda = 1.25$ GeV. The infrared (IR) cutoff μ and the constituent mass m must be fixed taking into account that CQM does not incorporate confinement. This means that one has to enforce the kinematical condition to produce free constituent quarks $M \geq m_Q + m$, where M is the mass of the heavy meson and m_Q is the constituent mass of the heavy quark. The heavy meson momentum is $P^\mu = m_Q v^\mu + k^\mu$, v^μ being the heavy quark 4-velocity and k^μ the so called residual momentum due to the interactions of the heavy quark with the light degrees of freedom at the scale of Λ_{QCD}. Therefore the above condition coincides with $v \cdot k \geq m$. This is so because the 4-velocity of the meson is almost coincident with that of the heavy quark, i.e. $P \simeq Mv$. Equivalently, in the rest frame of the meson, $\inf(k) = m$, meaning that the smallest residual momenta that can run in the CQM loop amplitudes are of the same size of the light constituent mass. The IR cutoff μ is therefore $\mu \simeq m$.

A reasonable constituent quark mass for the strange quark is $m = 510$ MeV/c^2, considering the ϕ meson as a pure $s\bar{s}$ state. Taking $\mu = 0.51$ GeV/c^2 as an infrared cutoff, a value of $m_0 = 131$ MeV/c^2 is required by the gap equation (consistently with the spread of values for the current s quark mass quoted in [29]). Varying the current strange mass in the range $60-170$ MeV/c^2 gives a small excursion of the constituent strange mass around the 500 MeV/c^2 value.

The free parameter of CQM is Δ_H defined, in the infinite heavy quark mass limit, by $\Delta_H = M_H - m_Q$. The subscript H refers to the $H-$multiplet of the HQET [18] $H = (0^-, 1^-)$. In a similar way a Δ_S is associated to the S multiplet, $S = (0^+, 1^+)$. The latter is determined by fixing Δ_H and solving the equation:

$$\Pi(\Delta_H) = \Pi(\Delta_S), \tag{7}$$

where

$$\Pi(\Delta_{H,S}) = I_1 + (\Delta_{H,S} \pm m) I_3(\Delta_{H,S}) \tag{8}$$

with

$$\begin{aligned} I_3(\Delta) &= -\frac{iN_c}{16\pi^4}\int^{\text{reg}} \frac{d^4k}{(k^2-m^2)(v\cdot k + \Delta + i\epsilon)} \\ &= \frac{N_c}{16\pi^{3/2}}\int_{1/\Lambda^2}^{1/\mu^2} \frac{ds\, e^{-s(m^2-\Delta^2)}}{s^{3/2}} \left(1 + \text{erf}(\Delta\sqrt{s})\right). \end{aligned} \tag{9}$$

Eq. (7) comes from requiring the HQET form of the kinetic term in the effective Lagrangian defining the model.

The related $\Delta_H^{(s)}, \Delta_S^{(s)}$ values in the strange sector are shown in Table I. We consider in the table the range of values $\Delta_H^{(s)} = 0.5, 0.6, 0.7$ GeV/c^2, which is consistent with the condition $M \geq m_Q + m$. Note that in the non strange sector we considered in [23] the values $\Delta_H = 0.3, 0.4, 0.5$ GeV/c^2, smaller or higher values being excluded by consistency argument or by experiment. Using (4) we see that the value $\Delta_H^{(s)} = 0.7$ GeV/c^2 has to be excluded as well.

$\Delta_H^{(s)}$	$\Delta_S^{(s)}$
0.5	0.86
0.6	0.91
0.7	0.97

TABLE I: $\Delta^{(s)}$ (in GeV/c^2).

In order to give the explicit value of the mass of the $(0^+, 1^+)$ states we observe that experimentally one has:

$$M_H^{(s)} = \frac{3M_{D_s^*} + M_{D_s}}{4} = 2076 \pm 1 \text{ MeV}/c^2. \tag{10}$$

Considering only the first two entries in Table I, from $\Delta_S^{(s)} - \Delta_H^{(s)} \equiv M_S^{(s)} - M_H^{(s)} = 335 \pm 25$ MeV/c^2 one gets

$$M_S^{(s)} = 2411 \pm 25 \text{ MeV}/c^2 \tag{11}$$

that differs by $\sim$140 MeV/c^2 from the rough estimate presented above.

Eq. (11) represents the main result of this note. It gives the average mass of the $S = (0^+, 1^+)$ doublet and is related to the masses of the two states by

$$M_S^{(s)} = \frac{3M_{D_s^*(1^+)} + M_{D_s(0^+)}}{4}. \tag{12}$$

From the measured value of the 0^+ state, eq. (1), we get

$$M_{D_s^*(1^+)} = \frac{4\, M_S^{(s)}}{3} - \frac{M_{D_s(0^+)}}{3} = 2442 \pm 33 \text{ MeV}/c^2, \tag{13}$$

which agrees, within the theoretical uncertainties, with the CLEO result (2). The overall agreement is better here than in other approaches, see e.g. the discussion contained in [16].

We note that in the present model the relation $(M_{1^+} - M_{0^+}) = (M_{1^-} - M_{0^-}) \simeq 142$ MeV/c^2 [9] does not hold necessarily (indeed we find $M_{1^+} - M_{0^+} = 125$ MeV/c^2). In any case, assuming its validity, from (3) we would get $M_{D_s^*(0^+)} = 2304 \pm 25$ MeV/c^2 and $M_{D_s^*(1^+)} = 2446 \pm 25$ MeV/c^2, which is also compatible, within the errors, with the data (1) and (2). Let us finally observe that, using Table I, we expect for the $B_s(0^+, 1^+)$ system a central mass of $M = 5740 \pm 25$ MeV/c^2 and, for the two individual states, $M_{B_s^*(0^+)} = 5710 \pm 25$ MeV/c^2 and $M_{B_s^*(1^+)} = 5770 \pm 25$ MeV/c^2 respectively. On the basis of these results, the $\bar{b}s$ signal at 5850 MeV/c^2 [29] should be better interpreted as arising from the $(1^+, 2^+)$ doublet predicted by the HQET.

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